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Auger recombination in a quantum well in a quantizing magnetic field

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Abstract. Basic mechanisms of Auger recombination of non-equilibrium carriers in quantum wells in the presence of a longitudinal quantizing magnetic field are studied. It is shown that two different recombination mechanisms are present: (i) a resonant non-threshold mechanism, (ii) a quasithreshold mechanism. The rate of the resonant Auger process depends on the temperature slightly but on the magnetic field essentially. For the quasithreshold Auger recombination process, the threshold energy depends on both the quantum well width and magnetic field. It is shown that the resonant Auger process dominates at low temperatures.

Introduction

In the homogenious semiconductors the mechanisms of Auger recombination in the presence of quantizing magnetic field have been studied by many authors [1-3]. At low temperatures the most probable phenomenon may be a resonant process of Auger recombination wherein two electrons and and a heavy hole (CHCC process) as well as an electron and two heavy holes (CHHS) participate. In the presence of of a strong magnetic field the electron spectrum is quantized [4]. As the result of Coulomb inter-action, the Auger electron havind acquired the energy of the order of E_g (the forbidden band gap) executes a vertical transfer to a high Landau level without a change in quasi-momentum. A large quasimomentum transfer is not required bacause of the Coulomb collision of two electrons. Thus, the Auger process has a resonant character in a quan-tizing magnetic field. The rate of the Auger process oscillates as a function of magnetic field, and these oscillations give rize to a break-down of the resonance.

The aim of the present paper is to study theoretically basic Auger recombination mechanisms in quantum wells in the presence of longitudinal qiantizing magnetic field. It is shown that in the undeep quantum wells ($E_g > U$, where U is the quantum well depth for electrons) there exist two different mechanisms of Auger recombination: (i) a resonant mechanism analogous to the Auger process in a homogenious semiconductor and (ii) a quasithreshold mechanism whose threshold energy depends on the quantum well width [5] and on the magnetic field. In the case of deep quantum wells ($E_g < U$) there exists only one mechanism of Auger recombination that is the resonant Auger process.

1 The rate of Auger recombination

The Auger transition rate for a two-dimensional carrier gas in the magnetic field is calcu-lated in the framework of first-order perturbation theory in electron-electron interaction:

$$G = \frac{2\pi}{\hbar} \sum_{1,2,3,4} |M|^2 \delta(E_1 + E_2 - E_3 - E_4) f_1^c f_2^c f_4^v (1 - f_3^c). \tag{1}$$

Here f^c and f^v are the Fermi distribution functions for electrons and holes, E_1 and E_2 are the initial, and E_3 and E_4 final, electron energy states (the hole state is treated as final one for one of the electrons participating in the process), summation in (1) is performed over all initial and final particle states including spins ones, M is the matrix element of Coulomb electron distribution, calculated with taking account for antisymmetrization of the electron wave functions in the initial and final states. The squared modulus of the matrix element is broken up into the sum of direct and exchange parts being equal to

$$|M|^2 = |M_I|^2 + |M_{II}|^2 - \{M_I M_{II}^* + M_I^* M_{II}\}, \qquad (2)$$

$$M_I = \frac{e^2}{\kappa} \sum_{\sigma,\sigma'} \iint d^3r\, d^3r'\, \psi_1^*(\mathbf{r},\sigma)\psi_2^*(\mathbf{r}',\sigma') \frac{1}{|\mathbf{r}-\mathbf{r}'|} \psi_3(\mathbf{r},\sigma)\psi_4(\mathbf{r}',\sigma'), \qquad (3)$$

$$M_{II} = \frac{4\pi e^2}{\kappa} \sum_{\sigma,\sigma'} \iint d^3r\, d^3r'\, \psi_1^*(\mathbf{r},\sigma)\psi_2^*(\mathbf{r}',\sigma') \frac{1}{|\mathbf{r}-\mathbf{r}'|} \psi_3(\mathbf{r}',\sigma')\psi_4(\mathbf{r},\sigma), \qquad (4)$$

where κ is the dielectric permeability constant, e is the electron charge. In the scope of Kane's model that will be used below, the quasiparticle wave function may be superposition of s- and p-type band states. It is convenient to use the basis $u_i(\mathbf{r}')(i = 1, 2, 3, \ldots, 8)$, where the conduction-band wave functions are spherical s-type functions, and those of valence band are eigenfunctions of the operators J^2 and J_z^2 (where J is the complete-moment operator). Then, using the Landau gauge ($A_x = -Hy, A_y = A_z = 0$ where A is the vector potential, and $H = (0, 0, z)$ is the magnetic field intensity), complete coordinate wave functions have the form

$$\psi(\mathbf{r}) = \varphi(x, z) \sum_i C_i \chi_{n_i}(y)\, u_i(\mathbf{r}). \qquad (5)$$

Here χ_{n_i} are the oscillation functions of the number n_i, $\varphi(x, z)$ is a smoothly varying envelope that depends on the coordinates (x, z), the coefficients C_i being functions of n_i and k_z.

The highly excited Auger electrons and holes are not localized in the Z-axis direction. We have $\varphi(x, z) = \exp(ik_x x + ik_z z)$ for those. For the electrons inside the well, $\varphi(x, z) = \exp(ik_x x) \cdot \tilde{\varphi}(z)$ where the form of $\tilde{\varphi}(z)$ depends on the profile of two-dimensional-electron potential well. For a rectangular well, $\tilde{\varphi}(x)$ is a linear combination of the functions $\sin k_z z$ and $\cos k_z z$. In the region of underbarrier motion of two-dimensional electrons which is of basic importance for a given problem, we have $\tilde{\varphi}(z) = \exp(-\kappa z)$, where $\kappa = \sqrt{2m_e U}$ is the damping index of the wave function under the barrier, m_e is the effective electron mass; and U is the barrier height.

We thus consider the Coulomb collision process for two electrons 1 and 2 with subsequent recombination of one of them with a hole and with the passage of the second electron onto a highly excited Landau level n_3. Then one should integrate in (3) and (4) not only over the well region, but over that of the whole narrow-gap semiconductor, *i.e.* we need integrate between $-\infty$ and $+\infty$. Then we substitute the Coulomb potential in the form of Fourier integral, and, replacing (5) into (3), we find

$$| M_I |^2 = \qquad (6)$$

$$= \frac{16\pi^2 e^4}{\kappa^2} \iint \frac{d^2q\, d^2q'\, \delta_{\sigma_1\sigma_2}\delta_{\sigma_2\sigma_4}}{(q^2 + k_{31x}^2 + \lambda^2)(q'^2 + k_{31x}^2 + \lambda^2)} \times$$

$$\times \, \delta(\mathcal{K}_x) q \mathcal{K}_{ii'}^{13}(\mathbf{q}, \mathbf{q}') \mathcal{K}_{jj'}^{24}(\mathbf{q}, \mathbf{q}'), \tag{7}$$

where

$$\delta(\mathcal{K}_x) = \delta(k_{1x} + k_{2x} - k_{3x} - k_{4x}),$$

$$\mathcal{K}_{ii'}^{13}(\mathbf{q}, \mathbf{q}') = [C_i^{*(1)} C_i^{(3)} I_i^{13}(\mathbf{q})][C_{i'}^{(1)} C_{i'}^{*(3)} I_{i'}^{13}(-\mathbf{q}')],$$

$$\mathcal{K}_{jj'}^{24}(\mathbf{q}, \mathbf{q}') = [C_j^{*(2)} C_j^{(4)} I_j^{24}(-\mathbf{q})][C_{j'}^{(2)} C_{j'}^{*(4)} I_{j'}^{24}(\mathbf{q}')],$$

$$k_{31x} = k_{3x} - k_{1x},$$

$$I_i^{\alpha\beta}(\mathbf{q}) = \int e^{iq_y y} \chi_{n_i}^{\alpha}(y) \, \alpha_{m_i}^{(\beta)}(y) \, dy \int e^{iq_z z} \varphi^{\alpha}(z) \, \varphi^{\beta}(z) \, dz,$$

λ is the Debye screening radius, $\mathbf{q}$ is the transmitted momentum, α and β denote particle state numbers ($\alpha, \beta = 1, 2, 3, 4$), $\delta_{\sigma_\alpha \sigma_\beta} = 1$ if $\sigma_\alpha = \sigma_\beta$, and $\delta_{\sigma_\alpha \sigma_\beta} = 0$ if $\sigma_\alpha \neq \sigma_\beta$. The remaining summands in (2) would be expressed in a similar way. Last, the matrix element $|M|^2$ should be substituted into (1) and summed over all particle states with regard to the energy conservation law, $E_1 + E_2 = E_3 + E_4$. Let the particles (electrons and holes) be at low Landau levels in their initial state. Then, their energies measured from the valence band top in Kane's model have the form

$$E_{1,2} = E_g + E_0 + \frac{4}{3} \frac{\gamma^2}{a_H^2 E_g} \left(\frac{1}{2} \mp \frac{1}{4} \right),$$

$$E_4 \equiv E_{hl} = -\frac{2}{3} \frac{\gamma^2}{E_g} \left[k_z^2 + \frac{2}{a_H^2} \left(\frac{1}{2} \mp \frac{1}{4} \right) \right].$$

Here $a_H = [\hbar c/(eB)]^{1/2}$ is the magnetic length, γ is Kane's matrix element, the signs "$\pm$" correspond to two spin directions. For simplicity, we consider recombination with light holes whose mass is $m_{hl} = m_e$. The Landau level $n_3 \gg 1$ corresponds to a highly excited electron, the spectrum of that electron is of the following nonparabolic form:

$$E_3(n_3) = E_g/2 + \left\{ (E_g/2)^2 \frac{2}{3} \gamma^2 \left[k_z^2 + \frac{2}{a_H^2} \left(n_3 + \frac{1}{2} \mp \frac{1}{4} \right) \right] \right\}^{1/2}. \tag{8}$$

Substituting E_2, E_2, E_3, and E_4 into the energy conservation law, we find the minimum value n_3^{min}:

$$n_3^{min} \simeq \frac{2E_g}{\hbar \omega}, \tag{9}$$

where $\omega = \frac{eH}{m_e c}$. While deriving (9), we have taken into account $\gamma k_z \ll E_g$ and $n_3 \gg 1$. We have also expressed Kane's matrix element γ through the effective electron mass: $\hbar^2/m_e = 4/3 \cdot \gamma^2/E_g$.

2   Results

Thus summing over the initial and final states in (1) with regard for the energy conservation law, we find the Auger-recombination time τ_{ee}^A:

$$1/\tau_{ee}^A = G/N_e = \frac{8\sqrt{3}(2\pi)^5}{2^{n_3}} \frac{E_B}{\hbar} \left(\frac{\hbar \omega E_0}{E_g^2} \right)^{1/2} \times$$

$$\tag{10}$$

$$\times \left(\frac{\lambda_{E_0}}{d} \right)^4 (\lambda_{E_0} \lambda_T)^{1/2} a_H^4 N_e N_h \psi(T, n_3).$$

Here N_e is the two-dimensional electron concentration, N_h is the tridimensional hole concentration; $E_B = \frac{me^4}{2\hbar^2\kappa^2}$ is the Bohr electron energy; the characteristic lenghs λ_{E_0}, and λ_T are equal to

$$\lambda_{E_0} = \left(\frac{\hbar^2}{2m_e E_0}\right)^{1/2}, \lambda_T = \left(\frac{\hbar^2}{2m_e T}\right)^{1/2}$$

respectively, d is the characteristic quantum-well width corresponding to the dimensional quantization energy E_0, $\psi(T, n_3)$ is a dimensionless function of the temperature and magnetic field equal to unity when the transition is resonant, and $\exp(-\frac{\hbar\omega}{3T})$ outside the resonance.

The oscillating behaviour of $1/\tau_{ee}^A$ as a function of magnetic field is an apparent result. When two electrons compile as Coulombian ones at the lowest Landau level, one of these passes into the valence band, another, absorbing the transmitted energy, turns into a highly excited state. The rate of such process is maximum if the highly excited electron exactly arrives at the Landau level of the number n_3, fitted the energy conservation law (formula (9)) (resonance transition), and small (or equal to zero at $T = 0$) if the highly excited electron has fallen between two Landau levels (non-resonant transition).

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